SUSYLR models & Consistent Cosmology

with gauge coupling unification & fermion mass universality

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Outline

The Standard Model SM

- Standard model is a gauge theory of three generations of chiral fermions based on the gauge group $SU(3)_c \times SU(2)_L \times U(1)_Y$. The fermion content is

$$Q_i = \begin{pmatrix} u \\ d \end{pmatrix} \sim (3, 2, \frac{1}{3}), \qquad L_i = \begin{pmatrix} \nu \\ e \end{pmatrix} \sim (1, 2, -1),$$

$$u_i^c \sim (3, 1, -\frac{4}{3}), \quad d_i^c \sim (3, 1, \frac{2}{3}), \quad e_i^c \sim (1, 1, 2)$$

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- *And so on..........*

Going beyond the SM

Some highly motivated extensions of the SM:

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- Incorporating additional flavour symmetries.
- *And Many Others....*

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- Supersymmetric version of such models come with other advantages like stabilizing scalar masses, natural dark matter candidate (LSP), gauge coupling unification etc.

R-PARITY

- R-parity is defined as $R_p = (-1)^{3(B-L)+2s}$. This is an ad-hoc symmetry in the Minimal Supersymmetric Standard Model(MSSM) to keep the B and L- violating terms away. LSP is stable in such scenario providing a cold dark matter candidate.
- R_p is not ad-hoc in SUSYLR models since it is a part of the gauge symmetry.
- Depending on the Higgs content of the model, R_p can remain conserved or get spontaneously violated.

Kuchimanchi Mohapatra (KM) Model

Particle content of this model is

$$\Phi_1 = \begin{pmatrix} \phi_{11}^0 & \phi_{11}^+ \\ \phi_{12}^- & \phi_{12}^0 \end{pmatrix} \sim (2,2,0), \quad \Phi_2 = \begin{pmatrix} \phi_{21}^0 & \phi_{21}^+ \\ \phi_{22}^- & \phi_{22}^0 \end{pmatrix} \sim (2,2,0),$$

$$\Delta = \begin{pmatrix} \delta_L^+/\sqrt{2} & \delta_L^{++} \\ \delta_L^0 & -\delta_L^+/\sqrt{2} \end{pmatrix} \sim (1,3,1,2),$$

$$\bar{\Delta} = \begin{pmatrix} \Delta_L^- \sqrt{2} & \Delta_L^0 \\ \Delta_L^{--} & -\Delta_L^-/\sqrt{2} \end{pmatrix} \sim (1,3,1,-2),$$

$$\Delta_c = \begin{pmatrix} \Delta_R^-/\sqrt{2} & \Delta_R^0 \\ \Delta_R^{--} & -\Delta_R^-/\sqrt{2} \end{pmatrix} \sim (1,1,3,-2),$$

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KM Model Contd...

- As shown by Kuchimanchi and Mohapatra in 1993, the above particle content gives rise to a D-parity preserving vacua.
- The above particle content with a parity odd singlet give rise to charge breaking vacua.
- However, if the right handed sneutrino acquires a vev, the above problems can be avoided and we can achieve spontaneous D-parity breaking.
- But R_p is spontaneouly broken in this model and hence cold dark matter candidate is lost.

Bound on M_R from Unification in KM Model

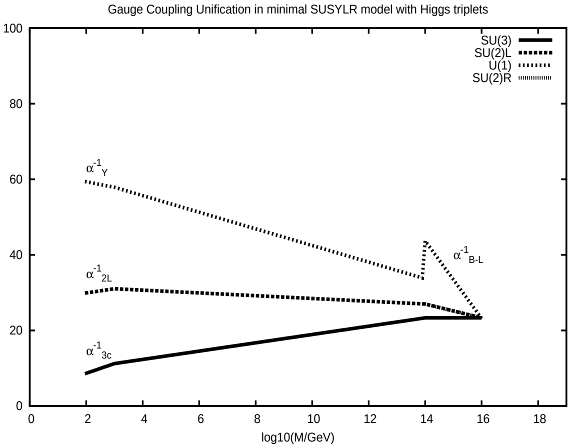

FIGURE: Gauge coupling unification with $M_{susy} = 1$ TeV, $M_R = 10^{14}$ GeV

ABMRS Model

- Aulakh et al proposed inclusion of two additional Higgs triplets Ω, Ω_c to achieve spontaneous D-parity breaking with conserved R_p unlike in the KM model. The Higgs content is

$$\Phi_1 \equiv (1,2,2,0), \quad \Phi_2 \equiv (1,2,2,0), \quad \triangle \equiv (1,3,1,2)$$

$$\bar{\triangle} \equiv (1,3,1,-2), \quad \triangle^c \equiv (1,1,3,-2), \quad \bar{\triangle}^c \equiv (1,1,3,2)$$

$$\Omega(1,3,1,0), \quad \Omega^c(1,1,3,0)$$

- The symmetry breaking sequence in this case is

$$SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L} \otimes D \quad \xrightarrow{\langle \Omega_c \rangle} \quad SU(2)_L \otimes U(1)_R \otimes U(1)_{B-L}$$

$$\xrightarrow{\langle \triangle_c \rangle} \quad SU(2)_L \otimes U(1)_Y$$

Unification Bound on M_R in ABMRS Model

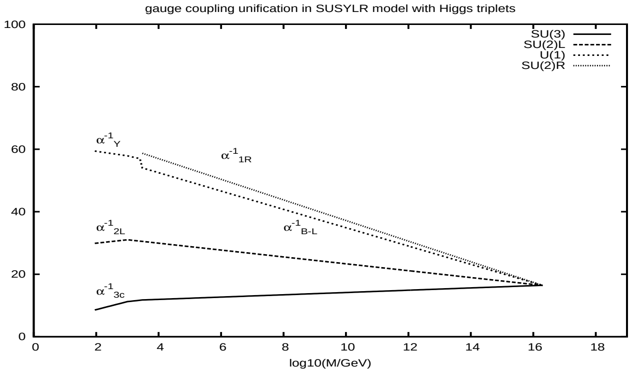

FIGURE: Gauge coupling unification in the ABMRS model with two extra pairs of superfields $\chi(3,1,1,-\frac{2}{3}), \bar{\chi}(\bar{3},1,1,\frac{2}{3})$ which decouple below M_{B-L}, $M_{SUSY} = 1$ TeV,$m_\Omega = M_{B-L} = 3$ TeV, $m_\triangle = M_R = M_{\rm GUT} = 2\times10^{16}$ GeV.

$b - \tau$ Unification in ABMRS Model

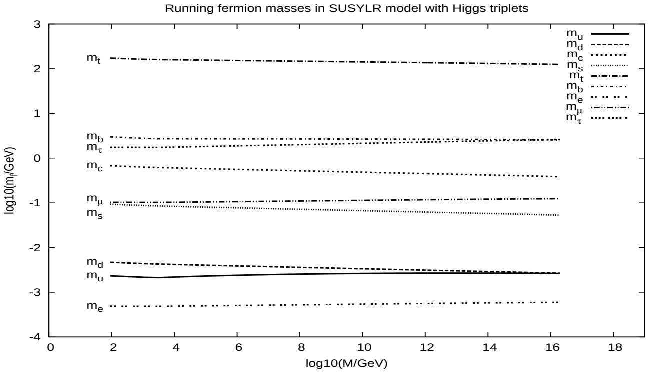

FIGURE: Running fermion masses in the ABMRS model with extra colored superfields $\chi_{1,2}(3,1,1,-\frac{2}{3})$, $\bar{\chi}_{1,2}(\bar{3},1,1,\frac{2}{3})$, $M_{SUSY} = 1$ TeV, $m_\Omega = M_{B-L} = 3$ TeV, $m_\triangle = M_R = M_{\text{GUT}} = 2 \times 10^{16}$ GeV and $|f| = 0.55, \tan\beta = 10$ at $M = M_Z$

The Bitriplet Model

- Higgs content of the model is

$$\Phi_1 \equiv (1,2,2,0), \quad \Phi_2 \equiv (1,2,2,0), \quad \triangle \equiv (1,3,1,2)$$

$$\bar{\triangle} \equiv (1,3,1,-2), \quad \triangle^c \equiv (1,1,3,-2), \quad \bar{\triangle}^c \equiv (1,1,3,2)$$

$$\eta(1,3,3,0), \quad \rho(1,1,1,0)$$

[1]

- The symmetry breaking sequence in this case is

$$SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L} \otimes D \quad \xrightarrow{\langle\rho\rangle} \quad SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$$

$$\xrightarrow{\langle\triangle_c\rangle} \quad SU(2)_L \otimes U(1)_Y$$

[1] S. Patra, A. Sarkar, U. Sarkar, and U. Yajnik, Phys. Lett. **B679**, 386(2009)

Unification bound on M_R in Bitriplet Model

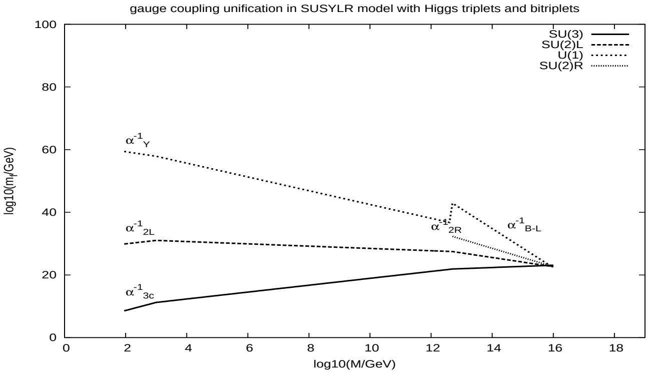

FIGURE: Gauge coupling unification in the bitriplet model with two extra pairs of superfields $\chi(3,1,1,-\frac{2}{3}), \bar{\chi}(\bar{3},1,1,\frac{2}{3})$ which decouple below M_R, $M_{susy} = 1$ TeV, $M_R = 5 \times 10^{12}$ GeV, $M_{\rm GUT} = M_\rho = 10^{16}$ GeV.

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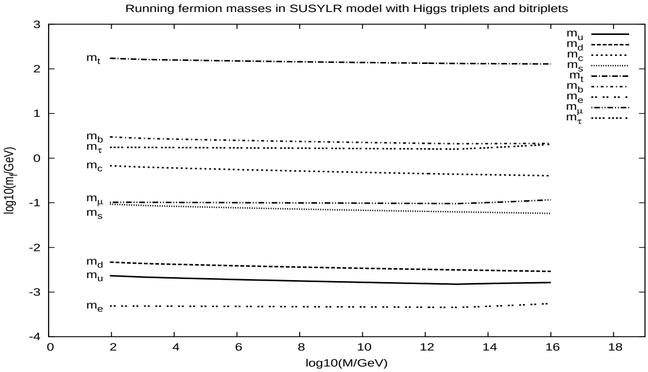

FIGURE: Fermion masses evolution in the bitriplet model with extra colored superfields $\chi_{1,2}(3,1,1,-\frac{2}{3})$, $\bar{\chi}_{1,2}(\bar{3},1,1,\frac{2}{3})$, $M_{susy} = 1$ TeV, $M_R = 5 \times 10^{12}$ GeV, $M_\rho = 10^{16}$ GeV and $|f| = 0.90, \tan\beta = 10$ at $M = M_Z$

Neutrino Mass in Higgs triplet Models

$$\begin{aligned}\mathcal{L}_{\nu}^{II} &= y_{ij}\ell_{iL}\Phi\ell_{jR} + y'_{ij}\ell_{iL}\tilde{\Phi}\ell_{jR} + h.c. \\ &+ f'_{ij}\ \left(\ell_{iR}^{T}\ C\ i\sigma_2\Delta_R\ell_{jR} + (R \leftrightarrow L)\right) + h.c.\end{aligned}$$

$$m_{\nu ij}^{I} = -(M_D M_R^{-1} M_D^T)_{ij}; \qquad m_{\nu ij}^{II} = f_{ij} v_L$$

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- In KM Model, seesaw is less trivial since the neutrinos mix with the neutralinos giving rise to a kind of double seesaw.

Minimal Higgs Doublet (MHD) Model

- Higgs content of the Model is:

$$H = \begin{pmatrix} H_L^+ \\ H_L^0/\sqrt{2} \end{pmatrix} \sim (2,1,1), \quad H_c = \begin{pmatrix} H_R^+ \\ H_R^0/\sqrt{2} \end{pmatrix} \sim (1,2,-1),$$

$$\bar{H} = \begin{pmatrix} h_L^0/\sqrt{2} \\ h_L^- \end{pmatrix} \sim (2,1,-1), \quad \bar{H}_c = \begin{pmatrix} h_R^0/\sqrt{2} \\ H_R^- \end{pmatrix} \sim (1,2,1),$$

$$\Phi_1(2,2,0), \quad \Phi_2(2,2,0)$$

- The symmetry breaking pattern is

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times D \xrightarrow{\langle H, H_c \rangle} SU(2)_L \times U(1)_Y$$

$$\xrightarrow{\langle \Phi \rangle} U(1)_{em}$$

Unification bound on M_R in MHD Model

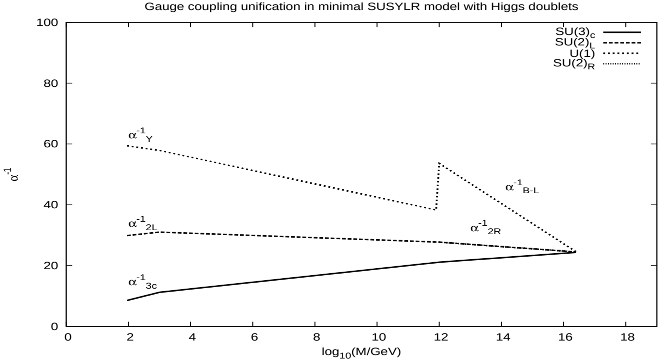

FIGURE: Gauge coupling unification in minimal SUSYLR model with Higgs doublets, $M_{susy} = 1$ TeV, $M_R = 10^{12}$ GeV, $M_{GUT} = 10^{16.4}$ GeV

Bhupal Dev Mohapatra (BDM) Model

The particle content of this model is same as the MHD Model except one additional parity odd singlet ρ. The symmetry breaking pattern is

$$SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L} \otimes D \quad \xrightarrow{\langle\rho\rangle} \quad SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$$

$$\xrightarrow{\langle H_c \rangle} \quad SU(2)_L \otimes U(1)_Y$$

Unification bound on M_R in the BDM Model

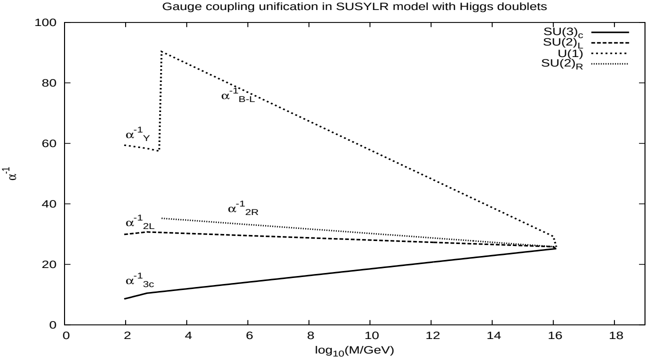

FIGURE: Gauge coupling unification in SUSYLR model with Higgs doublets and $M_{susy} = 500$ GeV, $M_R = 1.5$ TeV, $M_\rho = 10^{16}$ GeV

Unification in Higgs doublet model

$b-\tau$ Unification as well as gauge coupling unification in Higgs doublet model with parity odd singlet was shown by P. S. B. Dev and R. N. Mohapatra in Phys Rev **D81**,013001(2010).

Neutrino Mass in Higgs Doublet Models

Adding fermion triplets Σ_L, Σ_R for seesaw, the mass matrix in the basis $\left(\nu_L,\ \nu_R,\ \Sigma^0_R,\ \Sigma^0_L\right)$ reads as:

$$M^{III}_\nu = \begin{pmatrix} 0 & m^D_\nu & 0 & h v_L \\ (m^D_\nu)^T & 0 & g v_R & 0 \\ 0 & g^T v_R & M_\Sigma & 0 \\ h^T v_L & 0 & 0 & M_\Sigma \end{pmatrix}.$$

If one assumes $M_\Sigma >> g\, v_R >> m^D_\nu, h\, v_L$ one gets

$$m_{\nu_L} = \frac{1}{v_R^2\,(g^T g)}\left[m^D_\nu\, M_\Sigma\, (m^D_\nu)^T - v_R\, v_L\, m^D_\nu\, (g\, h)^T - v_R\, v_L\, (g\, h)\, (m^D_\nu)^T\right]$$

with right handed neutrino masses

$$M_R = v_R^2\, g\ (M_\Sigma)^{-1}\ g^T$$

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- Domain wall energy density decreases as $1/R$ (where R is the scale factor) which is slower than that of radiation and matter and hence the domain wall energy density may soon come to dominate the energy density of the Universe which is against observation.
- Thus there has to be some mechanism to make these Domain Walls unstable so that the phase transitions can occur successfully.

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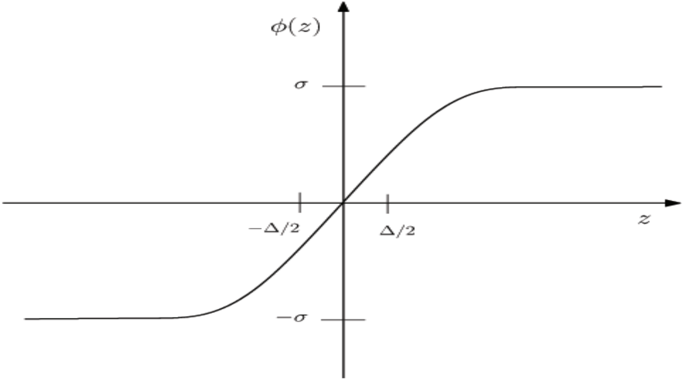

FIGURE: The solution of $\phi_w(z)$ for an infinite wall in the $x-y$ plane

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- The structure of these operators are dictated by supergravity and the gauge structure of the underlying theory.
- However, gravity can not distinguish between left and right sectors of the theory since the field content and the couplings are identical in both the sectors.

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- It was pointed out by Rai and Senjanovic in 1993 that Planck scale suppressed non-renormalizable operators can be a source of domain wall instability.
- The structure of these operators are dictated by supergravity and the gauge structure of the underlying theory.
- However, gravity can not distinguish between left and right sectors of the theory since the field content and the couplings are identical in both the sectors.
- One possible solution is to consider hidden sector origin of both D-parity and supersymmetry which get communicated to the visible sector via gravity.

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- Bound on the D-parity breaking scale is obtained from the successful disappearance of the walls.

Bound on M_R from Unification and Cosmology

TABLE: Bounds on M_R/GeV in R-parity violating SUSYLR models

Model	Unification	DW removal (MD era)	DW removal (RD era)	DW removal including WI
KM	$\geq 10^{14}$	$< 2.7 \times 10^5$	$< 10^7$	$\geq 1.4 \times 10^5 T_D^{12/13}$
MHD	$\geq 10^{12}$	$< M_{Pl}$	$< M_{Pl}$	$\geq 5.6 \times 10^4 T_D^{3/4}$
BDM	$\geq 1.5 \times 10^3$	None	None	None

Bound on M_R from Unification and Cosmology

TABLE: Bounds on M_R/GeV in R-parity conserving SUSYLR models

Model	Unification	DW removal (MD era)	DW removal (RD era)	DW removal including WI
ABMRS	$\geq 10^{15-16}$	$< 10^7$	$< 10^{11}$	$\geq 8.6 \times 10^4 \, T_D^{4/5}$
BM	$\geq 10^{14}$	None	None	None
Bitriplet	$\geq 5 \times 10^{12}$	None	None	None

Concluding Remarks

- Generic SUSYLR models with Higgs triplets having even $B - L$ charges are highly restrictive. Gauge coupling unification does not allow a low scale M_R in such models and forces M_R to remain very close to the GUT scale.
- In such models, successful removal of domain walls require M_R to be less than $10^9 - 10^{11}$ GeV, way below the GUT scale or the generic scale of inflation ($\sim 10^{16}$ GeV).
- Among the Higgs triplet models, the Bitriplet model is preferable since it satisfies both Unification and Cosmology bounds on M_R.

Concluding Remarks

- The Bitriplet Model can be realized within $SO(10)$ GUT models by simple extension of MSGUT (Minimal Supersymmetric GUT) with a **54** Higgs.
- MSGUT contains $\mathbf{10}, \mathbf{126}, \overline{\mathbf{126}}, \mathbf{210}$ Higgs representations and it was shown (PRD **70**, 035007 (2004)) that SUSYLR with broken D-parity can not be realized as an intermediate symmetry.
- We check that in MSGUT+ **54** it is possible to realize SUSYLR with broken D-parity as an intermediate symmetry.
- $b - \tau$ Unification for the doublet model shown by Dev and Mohapatra (Phys Rev **D81**, 013001 (2010)) can also be shown for the Bitriplet Model (Phys Rev **D83**, 095004(2011)).

Concluding Remarks

- SUSYLR models with Higgs doublets having odd $B-L$ charges opens up the possibility of a TeV scale M_R together with gauge coupling unification and tiny neutrino mass.
- Such models are also less restrictive from the requirement of domain wall disappearance. Any value of M_R from TeV scale to the Planck scale will guarantee domain wall disappearance in such models.

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THANK YOU